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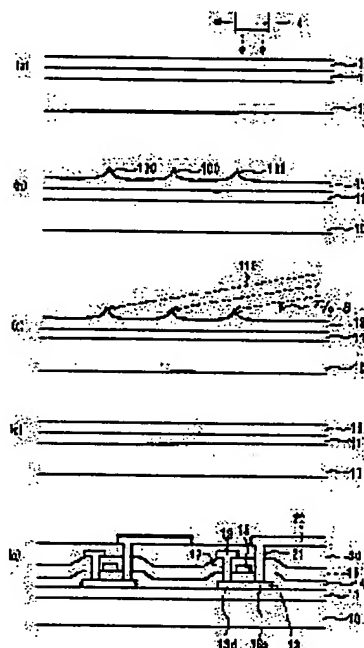
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(54) SEMICONDUCTOR DEVICE AND METHOD OF FABRICATION

(57)Abstract:

PROBLEM TO BE SOLVED: To provide a semiconductor device having good characteristics and a method of fabrication in which protrusions on a semiconductor film are polished to planarize the surface thereof.

SOLUTION: Protrusions 100 generated when an a-Si film 12 formed on an insulating substrate 10 is irradiated with laser light 14 to form a p-Si film 13 through fusion and recrystallization are irradiated with an ion beam of ion milling method at an incident angle of 60° -90° and removed. Since the surface of the p-Si film 13 is planarized, sufficient insulation can be ensured between the p-Si film 13 and a gate electrode 15.



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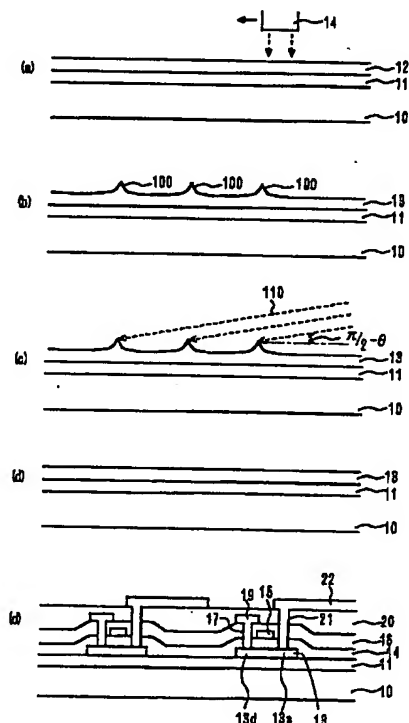
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(54) 【発明の名称】 半導体装置及びその製造方法

(57) 【要約】

【課題】 半導体膜に生じる突起を除去してその表面を平坦にし、良好な特性を有する半導体装置及びその製造方法を提供する。

【解決手段】 絶縁性基板 10 上に、a-Si 膜 12 を成膜し、その a-Si 膜 12 にレーザー光 14 を照射して熔融再結晶化して p-Si 膜 13 にした際に生じる突起 100 に対して、イオンミリング法によるイオンビームを入射角度 $60^\circ \sim 90^\circ$ で照射することにより、その突起 100 を除去してしまい、p-Si 膜 13 の表面を平坦にすることにより、p-Si 膜 13 とゲート電極 15 との間で十分な絶縁をとることができる。



【特許請求の範囲】

【請求項 1】 絶縁性基板上に非単結晶半導体膜を形成する工程と、該非単結晶半導体膜を加熱処理する工程と、該加熱処理により生じた前記非単結晶半導体膜の突起を物理的除去方法により除去する工程と、を備えたことを特徴とする半導体装置の製造方法。

【請求項 2】 前記加熱処理工程は、レーザ光を照射して溶融再結晶化させる工程であることを特徴とする請求項 1 に記載の半導体装置の製造方法。

【請求項 3】 前記物理的除去方法は、イオンミリングのイオンビームを前記突起に対して照射して除去する方法であることを特徴とする請求項 1 又は 2 に記載の半導体装置の製造方法。

【請求項 4】 前記イオンミリングのイオンビームの入射方向と、前記非単結晶半導体膜面に対する垂線との成す角 θ が、 $60^\circ \sim 90^\circ$ であることを特徴とする請求項 3 に記載の半導体装置の製造方法。

【請求項 5】 絶縁性基板上に形成した非単結晶半導体膜を加熱処理した際に生じる前記非単結晶半導体膜の突起をイオンビームを照射することにより除去することによって、前記非単結晶半導体膜の表面が平坦であることを特徴とする半導体装置。

【発明の詳細な説明】

【0001】

【発明の属する技術分野】 本発明は、半導体装置及びその製造方法に関し、半導体膜の表面を平坦にした半導体装置及びその製造方法に関する。

【0002】

【従来の技術】 以下に、従来の薄膜トランジスタ (Thin Film Transistor、以下、「TFT」と称する。) の製造方法について説明する。

【0003】 図 7 に多結晶化された多結晶シリコン膜の表面状態を示し、図 8 に図 7 中の A-A 線に沿った従来の薄膜トランジスタの製造工程断面図を示す。

【0004】 工程 1 (図 8 (a)) : ガラス、石英ガラス等から成る絶縁性基板 10 上に、非晶質シリコン膜 (以下、「a-Si 膜」と称する。) 11 を CVD 法を用いて成膜する。

【0005】 工程 2 (図 8 (b)) : その a-Si 膜 10 に XeCl、KrF、ArF などの線状のエキシマレーザ 14 を一方から他方に向かって走査しながら照射してアニール処理を行って、a-Si 膜 12 を溶融再結晶化し多結晶化させて多結晶シリコン膜 (以下、「p-Si 膜」と称する。) 13 にする。

【0006】 このとき、a-Si 膜 12 の表面にエキシマレーザビーム 14 を矢印方向に走査しながら照射することにより a-Si 膜 12 が溶融されて再結晶化が進む。即ち、レーザ照射 14 によって加熱された a-Si 膜 12 は溶融した後に冷却されて再結晶化されて p-Si 膜となる。ところが、その際に各結晶の粒界がぶつか

りあってその箇所が隆起して突起 100 が生じてしまう。

【0007】 工程 3 (図 8 (c)) : p-Si 膜 13 上に、CVD 法にて SiO₂ 膜から成るゲート絶縁膜 14 を全面に形成する。そして、クロム (Cr)、モリブデン (Mo) などの高融点金属からなる金属膜をスパッタ法を用いて形成し、ホトリソグラフィ技術及び RIE (Reactive Ion Etching: 活性化イオンエッチング) 法によるドライエッチング技術を用いて所定形状に加工して、ゲート電極 15 を形成する。

【0008】 そして、Pチャネル型の TFT を形成する場合には、ゲート電極 15 をマスクとして、ゲート絶縁膜 14 を介して p-Si 膜 13 に対してボロン (B) 等の P 型イオンを注入し、Nチャネル型の TFT を形成する場合には、リン (P) 等の N 型イオンを注入する。これにより、能動層である p-Si 膜 13 のゲート電極 15 で覆われた部分がチャネル領域 13c となり、その両側の部分がソース領域 13s 及びドレイン領域 13d となる。

【0009】 その後、CVD 法を用いて SiO₂ 膜単体、又は SiO₂ 膜と SiN 膜との 2 層からなる層間絶縁膜 16 を形成する。

【0010】 工程 4 (図 8 (d)) : そして、ドレイン領域 13d に対応した位置に層間絶縁膜 16 及びゲート絶縁膜 14 を貫通する第 1 のコンタクトホール 17 を p-Si 膜 13 に到達するように形成し、この第 1 のコンタクトホール 17 部分に、アルミニウム等の金属からなるドレイン電極 19 を形成する。このドレイン電極 19 の形成は、例えば、第 1 のコンタクトホール 17 が形成された層間絶縁膜 16 上にスパッタリングして堆積するとともに第 1 のコンタクトホール 17 に充填したアルミニウムをパターニングすることで形成される。

【0011】 そして、ドレイン電極 19 が形成された層間絶縁膜 16 及びドレイン電極 19 上に平坦化絶縁膜 20 を形成して表面を平坦化する。この平坦化絶縁膜 20 は、アクリル樹脂溶液を塗布し、焼成してアクリル樹脂層を形成してなっており、このアクリル樹脂層は、ゲート電極 15、ドレイン電極 19 による凹凸を埋めて表面を平坦化することができる。

【0012】 さらに、ソース領域 13s 上に平坦化絶縁膜 20 であるアクリル樹脂層、層間絶縁膜 16 及びゲート絶縁膜 14 を貫通する第 2 のコンタクトホール 21 を形成し、この第 2 のコンタクトホール 21 部分に、ソース 13s に接続されてアクリル樹脂層上に広がる表示電極 22 を形成する。この表示電極 22 は、第 2 のコンタクトホール 21 が形成された平坦化絶縁膜 15 上に透明導電膜、例えば ITO (Indium Thin Oxide: 酸化インジウム錫) を積層し、そして、その透明導電膜上にレジスト膜を塗布した後、所定の電極パターンを形成し、エッチングガスとして、HBr ガス及び Cl₂ を用いてド

ライエッチング法、例えばRIE法によって露出した透明導電膜をエッチングすることにより形成される。

【0013】

【発明が解決しようとする課題】ところが、上述のように製造したTFTによれば、レーザビーム照射によってa-Si膜が熔融再結晶化される際に、各結晶の粒界がぶつかりあってその箇所が隆起して生じたp-Si膜13表面の突起100の上層に形成したゲート絶縁膜14の厚みが突起100が生じた箇所においては薄くなってしまうことになる。この突起100は、p-Si膜13の厚みが約400Åの場合に、その厚みと同じく約400Åにもなってしまう。このため、p-Si膜13とゲート電極15との間で十分な絶縁をとることができない、あるいは突起100の高さがゲート絶縁膜14の厚みよりも大きい場合にはp-Si膜13とゲート電極15とが短絡してしまうという欠点があった。

【0014】また、突起100には印加された電圧によって電界が集中してしまい、やはり絶縁破壊を起こしてしまい、p-Si膜13とゲート電極15とが短絡してしまうという欠点があった。

【0015】更に、ゲート電極15に印加された電圧のp-Si膜13に対して印加される電圧が絶縁性基板面内ではばらつきが生じてしまうことになり、結果として特性の不均一なTFTが形成されてしまうという欠点があった。そのTFTを液晶表示装置等の表示装置に採用した場合には、表示画面内においてばらつきが生じてしまうという欠点もあった。

【0016】そこで、本発明は、上述の欠点に鑑みて為されたものであって、半導体膜に生じる突起を除去してその表面を平坦にし、良好な特性を有する半導体装置及びその製造方法を提供することを目的とする。

【0017】

【課題を解決するための手段】本発明の半導体装置の製造方法は、絶縁性基板上に非単結晶半導体膜を形成する工程と、該非単結晶半導体膜を加熱処理する工程と、該加熱処理により生じた前記非単結晶半導体膜の突起を物理的除去方法により除去する工程と、を備えたものである。

【0018】また、上述の半導体装置の製造方法は、前記加熱処理工程は、レーザ光を照射して熔融再結晶化させる工程である半導体装置の製造方法である。

【0019】また、上述の半導体装置の製造方法は、前記物理的除去方法が、イオンミリングのイオンビームを前記突起に対して照射して除去する方法である半導体装置の製造方法である。

【0020】更に、前記イオンミリングのイオンビームの入射方向と、前記非単結晶半導体膜面に対する垂線との成す角 θ が、 $60^\circ \sim 90^\circ$ である半導体装置の製造方法である。

【0021】また、本発明の半導体装置は、絶縁性基板

上に形成した非単結晶半導体膜を加熱処理した際に生じる前記非単結晶半導体膜の突起をイオンビームを照射することにより除去することによって、前記非単結晶半導体膜の表面が平坦である半導体装置である。

【0022】

【発明の実施の形態】以下に、本発明の半導体装置の製造方法をTFTを備えた液晶表示装置に採用した場合について説明する。

【0023】図1に、本発明のTFTの製造工程断面図を示し、図2に液晶表示装置の断面図を示す。

【0024】工程1（図1（a））：ガラス、石英ガラス等から成る絶縁性基板10上に、SiO₂膜単体、あるいはSiN膜及びSiO₂膜から成る絶縁性膜11をCVD法等を用いて形成する。これは、絶縁性基板からのナトリウム（Na）イオン等の不純物がその上に形成する半導体膜（p-Si膜）に浸入することを防止するためである。不純物が浸入する恐れがない無アルカリガラス基板等を用いる場合には必ずしも必要ではない。

【0025】また、本発明においては、絶縁性基板は、表面が絶縁性を呈する基板も含むものとする。即ち、半導体基板上にSiN膜及びSiO₂膜から成る絶縁性膜11を堆積したものであっても良い。

【0026】絶縁膜11上に、a-Si膜12をCVD法を用いて成膜する。そのa-Si膜12の膜厚は、300～1000Åであり、本実施の形態においては400Åとした。

【0027】工程2（図1（b））：そのa-Si膜12に波長が308nmで線状のエキシマレーザを一方から他方に向かって走査しながら照射してアニール処理を行って、a-Si膜12を熔融再結晶化し多結晶化させて多結晶シリコン膜（以下、「p-Si膜」と称する。）13にする。

【0028】このとき、a-Si膜の表面にエキシマレーザビームを照射することによりa-Si膜が熔融されて再結晶化が進む。即ち、レーザ照射によって加熱されたa-Si膜は熔融した後に冷却されて再結晶化されるが、その際に各結晶の粒界がぶつかりあってその箇所が隆起して突起100が生じてしまう。

【0029】レーザビームとしては、波長 $\lambda = 308$ nmのXeClエキシマレーザを使用してもよく、また、波長 $\lambda = 193$ nmのArFエキシマレーザを使用してもよい。

【0030】工程3（図1（c））：次に、イオンミリング装置からのイオンビーム110を照射してその突起100をエッチングする。

【0031】p-Si膜の突起100をエッチングするために、p-Si膜13の表面に対して角度 θ の角を成す方向からArイオン照射110をする。

【0032】工程4（図1（d））：そうして、p-Si膜13の表面の突起100を除去して、p-Si膜1

3表面を平坦にする。

【0033】工程5(図1(e)): p-Si膜13上に、CVD法にてSiO₂膜から成るゲート絶縁膜14を全面に形成する。そして、Cr、Moなどの高融点金属からなる金属膜をスパッタ法を用いて形成し、ホトリソグラフィ技術及びRIE法によるドライエッチング技術を用いて所定形状に加工して、ゲート電極15を形成する。

【0034】そして、ゲート電極15をマスクとして、ゲート絶縁膜14を介してp-Si膜13にP型またはN型のイオンを注入する。即ち、形成すべきTFTのタイプに応じて、ゲート電極15に覆われていないp-Si膜13にP型またはN型のイオンを注入する。

【0035】Pチャネル型のTFTを形成する場合には、ボロン(B)等のP型イオンを注入し、Nチャネル型のTFTを形成する場合には、リン(P)等のN型イオンを注入する。これにより、能動層であるp-Si膜13のうちゲート電極15で覆われた部分がチャネル領域13cとなり、その両側の部分がソース領域13s及びドレイン領域13dとなる。

【0036】その後、CVD法を用いて、SiO₂膜単体、又はSiO₂膜とSiN膜との2層からなる層間絶縁膜16を形成する。

【0037】そして、ドレイン領域13dに対応した位置に層間絶縁膜16を貫通する第1のコンタクトホール17をp-Si膜13に到達するように形成し、この第1のコンタクトホール17部分に、アルミニウム等の金属からなるドレイン電極19を形成する。このドレイン電極19の形成は、例えば、第1のコンタクトホール17が形成された層間絶縁膜16上にスパッタリングして堆積するとともに第1のコンタクトホール17に充填したアルミニウムをパターニングすることで形成される。

【0038】次いで、ドレイン電極19が形成された層間絶縁膜16及びドレイン電極19上に平坦化絶縁膜20を形成して表面を平坦化する。この平坦化絶縁膜20は、アクリル樹脂溶液を塗布し、焼成してアクリル樹脂層を形成してなっており、このアクリル樹脂層は、ゲート電極15、ドレイン電極19による凹凸を埋めて表面を平坦化することができる。

【0039】さらに、ソース領域13s上に平坦化絶縁膜20であるアクリル樹脂層、層間絶縁膜16及びゲート絶縁膜14を貫通する第2のコンタクトホール21を形成し、この第2のコンタクトホール21部分に、ソース領域13sに接続されてアクリル樹脂層上に広がる表示電極22を形成する。この表示電極22は、第2のコンタクトホール21が形成された平坦化絶縁膜20上に透明導電膜、例えばITOを積層し、そして、その透明導電膜上にレジスト膜を塗布した後、所定の電極パターンを形成し、エッチングガスとしてHBrガス及びCl₂ガスを用いてドライエッチング法、例えばRIE法によ

って露出した透明導電膜をエッチングすることにより形成される。

【0040】そして、表示電極22及び平坦化絶縁膜20上に、ポリイミド、SiO₂等からなり、液晶24を配向させる配向膜23を、印刷法またはスピンナー法にて形成する。

【0041】こうして、液晶を駆動させるTFTをスイッチング素子とした液晶表示装置の片側のTFT基板10が完成する。

【0042】次に、石英ガラスまたは無アルカリガラスからなる絶縁基板である対向電極基板30上に、この基板30側から順にITO膜等の透明導電膜からなる対向電極31を基板全面に形成した後、その上に液晶24を配向するためのポリイミド、SiO₂等からなる配向膜32を形成する。

【0043】こうして、上述のTFT基板10に対向して対向電極基板30を設け、TFT基板10と対向電極基板30との間であってそれらの周辺に、接着性を有する樹脂からなるシール剤を用いて両基板10、30を接着し、両基板間10、30に液晶24を充填して、図2に示すような液晶表示装置が完成する。

【0044】ここで、p-Si膜13表面に生じた突起100を除去するイオンミリング装置の原理について説明する。

【0045】図3に、イオンミリング装置の概略断面図を示す。

【0046】同図に示すように、イオンミリング装置は、イオンを発生させるイオン発生領域ISと、被照射物にイオンを照射して被エッチング物のエッチングを行うエッチングチャンバ領域ECとから成っている。いずれの領域ともに真空にしてありその真空度は1E(-6) Torrである。

【0047】一方のイオン発生領域ISには、マグネットによってイオン化されるガス、例えばアルゴン(Ar)ガスを供給するガス供給口210と、そのガスをプラズマ化するための磁界を発生させるマグネット230が周りに配置された円筒形状のアノード231と、熱電子を放出するフィラメントからなるカソード240とを備えている。また、発生されたプラズマ中からArイオンを引き出す引き出し電極250を備えている。

【0048】他方のエッチングチャンバ領域ECは、引き出し電極250によって引き出されたArイオンを中性化するための電子を放出するニュートライザ260を備えている。また、被エッチング物を固定するステージ290が備えられている。排気口300より排気される。

【0049】ステージ290には被エッチング物であるp-Si膜280を全面に形成したガラス基板270が固定してあり、ステージ290は所定の速度で回転される。回転させることによりガラス基板270上のp-S

i膜280に均一にAr原子が照射110されるようにしている。また、イオン源発生領域ISから照射されるAr原子の入射方向は、ステージ270表面の垂線から角度 θ だけ傾いている。即ち、p-Si膜280面に対して角度 $(\pi/2 - \theta)$ を成す方向からp-Si膜280にAr原子が入射される。こうして、p-Si膜280に発生した突起100に対して一定の角度 θ からAr原子260が照射されるように配置されて、突起100がエッチングされる。この角度 θ は、ステージ290の固定角度を調整することにより、任意に変えることが可能である。

【0050】上述のイオンミリング装置において、イオン発生源領域IS及びエッチングチャンバ領域EC内を拡散ポンプ等により真空にする。そしてガス供給口210からArガスをイオン発生源領域IS内に供給し、アノード電極231、マグネット230及びカソード240に電圧を印加して、Arガスをプラズマ化する。そのプラズマ中のArイオンをエッチングチャンバ領域ECに引き出すために、引き出し電極250に約800Vの電圧を印加してArイオンを引き出す。そしてこの引き出されたArイオンにニュートライザ260からの電子を供給して、Arイオンに電子を結合させてAr原子とする。そして、そのAr原子110をステージ290に固定されたガラス基板270上のp-Si膜280に衝突させる。このAr原子260がp-Si膜280表面に発生した突起100に衝突して除去させる。

【0051】ここで、突起100のAr原子によるエッチングについて説明する。

【0052】図4に、各形状の突起に対してAr原子を照射してエッチングする様子を示す。

【0053】図4(a)には円錐状の突起の場合を、図4(b)には円錐形状の複数個連続した突起の場合を、図4(c)には長方形の形状をした突起の場合を示す。

【0054】まず、図4(a)に示す円錐形状の突起の場合について説明する。

【0055】ここで、突起100はp-Si膜280の表面に対して角度 α の仰角をもってなっているとし、また、Ar原子110は、p-Si膜13表面に対して垂直な垂線VL1から角度 θ だけ傾いた方向から入射すると仮定する。

【0056】すると、円錐形状の突起100の斜面に対して垂直な垂線VL2から角度 $(\theta - \alpha)$ だけ傾いた方向からAr原子が入射することになる。斜面ではあるが、面に対して言えば、p-Si表面の平面に入射されることになる。

【0057】このとき、p-Si膜280を形成したガラス基板10は、ステージ290に固定されており、ステージとともに回転しているのでp-Si膜280の全面に均一にAr原子が照射されることになる。従って、このAr原子が次々とp-Si膜13の突起部の斜面及

びそれ以外の平坦部に照射されることにより、突起部以外の平坦部よりも突起100aが速くエッチングされていき、次第に突起100b、突起100cへと形状が小さくなって突起を除去することができる。従って、表面の平坦なp-Si膜13を得ることができる。

【0058】次に、円錐形状の複数個連続した突起の場合について説明する。

【0059】図4(a)に示した突起の除去と同様に、突起100はp-Si膜13の表面に対して角度 α の仰角をもってなっているとし、また、Ar原子110は、p-Si膜13表面に対して垂直な垂線VL1から角度 θ だけ傾いた方向から入射すると、円錐形状の突起100の斜面に対して垂直な垂線VL2から角度 $(\theta - \alpha)$ だけ傾いた方向からAr原子が入射することになる。そして、100a、100b、100cの順に突起がエッチングされていき、表面を平坦にすることができる。

【0060】次に、図4(c)に示す円柱の形状をした突起の場合について説明する。

【0061】同図において、突起100はp-Si膜13の表面に対して垂直に突起しているものとし、またAr原子110は、p-Si膜13の突起100の表面に対して垂直な垂線VL1から角度 θ だけ傾いた方向から入射されるものとする。

【0062】そうすると、p-Si膜13上面に対して垂直な側面VSに対しては、Ar原子110は、その側面VSに対して垂直な垂線VL2に対して角度 $(\pi/2) - \theta$ だけ傾いた方向から入射することになる。側面VSもその面は平坦な表面であると言える。

【0063】こうして、このAr原子が次々とp-Si膜13に照射されることにより、この突起の上面よりも側面VSのほうがエッチングされながら突起100aから次第にエッチングされていき、突起100b、突起100cへと形状が小さくなって突起を除去することができる。従って、表面の平坦なp-Si膜13を得ることができる。

【0064】ここで、p-Si膜にAr原子を照射した場合のAr原子の照射角度とp-Si膜のエッチングレートとの関係について説明する。

【0065】図5に、平坦な表面のp-Si膜にAr原子を照射した場合のAr原子の照射角度とp-Si膜のエッチングレートとの関係を示す。なお、同図において、横軸は照射されるAr原子のp-Si膜面の垂線からの角度を示し、縦軸にそのAr原子によってエッチングされるp-Si膜のエッチングレートを示す。

【0066】同図に示すように、Ar原子(Arイオンビーム)入射方向によってシリコンのエッチングレートは異なる。なお、同図は、Ar原子のビームエネルギーは500eV、Ar原子の電流密度は1.4mA/cm²の場合を示している。

【0067】エッチングレートは、Ar原子入射角度 θ

が 0° から大きくなるにつれて徐々になだらかに上昇し、 60° で最大となり、 60° から 90° 近傍にかけては急激に減少する。

【0068】前述の図4(a)に示した円錐形状の突起の場合について、再度説明する。突起をイオンビームを照射して除去する場合、突起部のエッチングレートは大きく、平坦な部分のエッチングレートは小さいことが好ましい。即ち、図4(a)に示す円錐形状の場合においても、突起部100aは早くエッチングされ、また平坦な部分はエッチングされにくいことが好ましい。

【0069】ここで、例えば、イオンビームの入射角度 θ が 88° で、円錐形状の突起のp-Si膜13の表面に対する角度 α が 60° の場合を考える。

【0070】即ち図4(a)において垂線VL1からの角度 θ が 88° であり、その方向からイオンビームが入射してp-Si膜280の平坦な部分に照射される。また、p-Si膜280の表面(このとき円錐形状の側面は斜面であるが、その斜面自体は平坦な部分である。)に対する垂線VL2からの角度($\theta - \alpha$)は 28° (= $88^\circ - 60^\circ$)である。この場合を図5で見ると、平坦な表面のp-Si膜に照射したときに、入射角度が 88° の場合にはエッチングレートは約 $100\text{Å}/\text{min}$ であり、入射角度が 28° の場合にはエッチングレートは約 $600\text{Å}/\text{min}$ である。即ち、平坦な部分のエッチングレート(約 $100\text{Å}/\text{min}$)に対して突起部のエッチングレート(約 $600\text{Å}/\text{min}$)であるので、突起部分は平坦な部分に比べて約6倍のエッチングレートでエッチングされていくため、平坦部が多くエッチングされてしまうことなく、突起部のエッチングが完了することになる。

【0071】なお、図4に示した他の突起の形状の場合においても同様に、平坦部のエッチングレートに比べて、突起部のエッチングレートが大きくなるようにイオンビームの入射角度を選択することにより、平坦部分がエッチングされてしまうことなく効率よく突起部をエッチングすることができる。

【0072】また、図6に、p-Si膜にAr原子を照射した後のp-Si膜上の突起の状態の一例を示す。同図において、横軸は基板の表面の垂線からの角度を示し、縦軸はAr原子照射後のp-Si膜上の突起の平均高さを示している。なお、突起の平均高さは 400Å の場合を示しており、形状は概ね図6中に示した円錐形状をしている場合である。

【0073】同図に示すように、入射角度が大きくなるにつれて突起の高さは低くなる、即ち除去されてp-Si膜の表面が平坦になってくることがわかる。

【0074】ここで、能動層であるp-Si膜の突起は、その上に形成する絶縁膜を突き抜けてしまうと絶縁性が得られないどころか、その絶縁膜上の導電層とショートしてしまうことになるので、高くないことが望まし

い。p-Si膜の突起の残りとしては、概ね絶縁性を保持できる程度の厚みであればよい。

【0075】以上のことから、突起残りが 250Å であれば良いことから入射角度が 60° であれば良い。また、突起残りが 200Å であれば更に好ましいことから入射角度が 70° であれば良い。更に好ましくは突起残りが 150Å であれば更に好ましいことから入射角度が 80° であれば良い。

【0076】以上のように、p-Si膜の表面に生じた突起をイオンミリング法によってイオンビームを照射して表面を平坦にすることにより、p-Si膜13とゲート電極15との間で十分な絶縁をとることができるとともに、突起100の高さがゲート絶縁膜14の厚みよりも大きい場合にも、研磨によって平坦にすることによりp-Si膜13とゲート電極15とが短絡してしまうことがない。

【0077】また、突起100には印加された電圧によって電界が集中してしまうこともない。

【0078】更に、ゲート電極15に印加された電圧のp-Si膜13に対して印加される電圧が絶縁性基板面内ではばらつきが生じて、結果として特性の不均一なTFTが形成されてしまうこともない。そしてそのTFTを液晶表示装置等の表示装置に採用した場合にも、表示画面内においてばらつきが生じてしまうこともない。

【0079】なお、本発明は、ステージ290に固定したガラス基板270は、上述の実施の形態に示したように1つの液晶表示パネルをなすガラス基板を固定することに限定されるものではなく、1枚のガラス基板に多数の液晶表示パネルを備えたいわゆるマザーガラス基板であっても同様の効果が得られるものである。

【0080】

【発明の効果】本発明によれば、イオンミリング法を用いて効率よくp-Si膜の表面に発生する突起を除去して平坦な表面にすることができるので、良好な特性の半導体装置を得ることができる。

【図面の簡単な説明】

【図1】本発明の半導体装置の製造方法の製造工程断面図である。

【図2】本発明の半導体装置を液晶表示装置に採用した場合の断面図である。

【図3】本発明の半導体装置の製造方法に用いるイオンミリング装置の断面図である。

【図4】本発明の半導体装置の製造方法のエッチング工程断面図である。

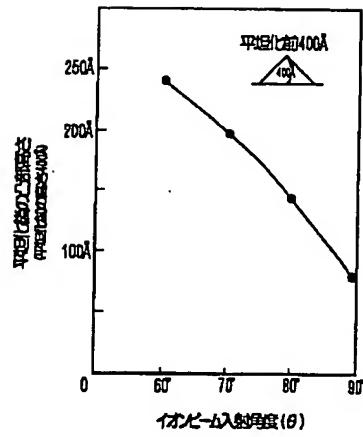
【図5】本発明のイオンビーム入射角度とエッチングレートとの関係を示す特性図である。

【図6】本発明のイオンビーム入射角度と平坦化後の突起の高さとの関係を示す図である。

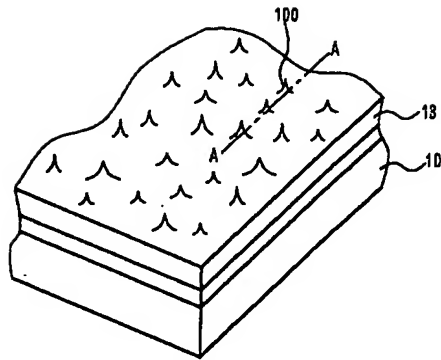
【図7】従来の半導体装置の表面状態を示す図である。

【図8】従来の半導体装置の製造方法の製造工程断面図

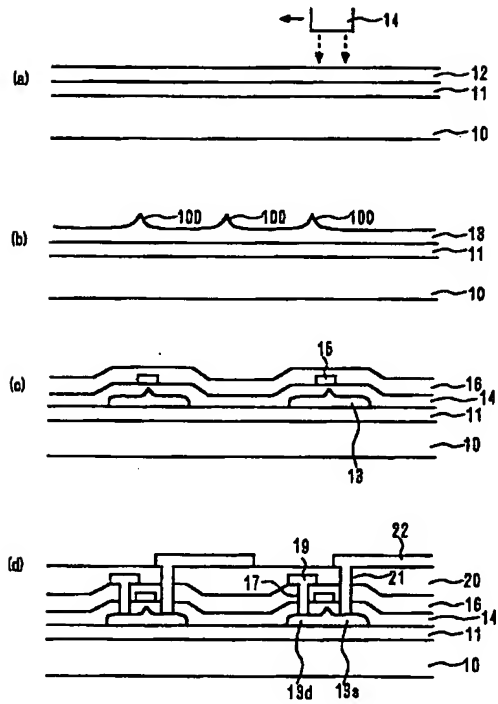
【図6】



【図7】



【図8】



フロントページの続き

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DD14 DD17 EE04 FF02 FF29
GG02 GG13 GG25 GG44 GG58
HJ13 HL03 HL07 HL23 NN03
NN23 NN24 NN27 NN35 NN36
NN72 PP03 PP04 PP38 QQ11
QQ19



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(54) **ADAPTIVE GCIB FOR SMOOTHING SURFACES**

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(52) U.S. Cl. **156/345; 118/723 CB; 315/111.81**

(58) Field of Search **156/345; 118/723 CB; 315/111.81**

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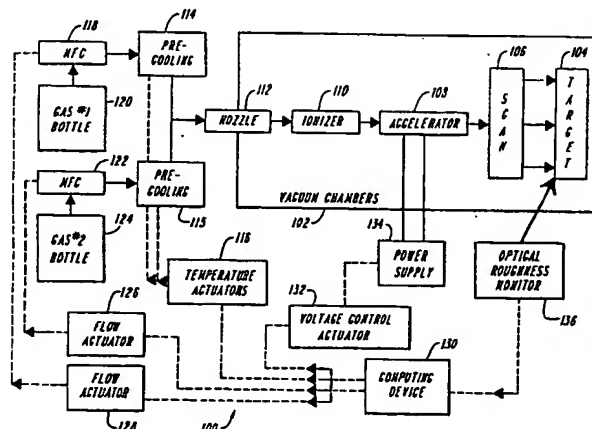
Primary Examiner—Jeffrie R. Lund

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(57) **ABSTRACT**

A method and apparatus for adapting the nature of an ion beam during processing of the surface of a solid workpiece so as to improve the reduction of surface roughness (smoothing) by using a GCIB. In addition, the invention provides for surface smoothing in combination with etching to predetermined depths and surface contamination removal. Advantages are minimum required processing time, minimum remaining roughness of the final surface, and reduction in the amount of material that must be removed in order to attain a desired level of smoothness.

9 Claims, 2 Drawing Sheets

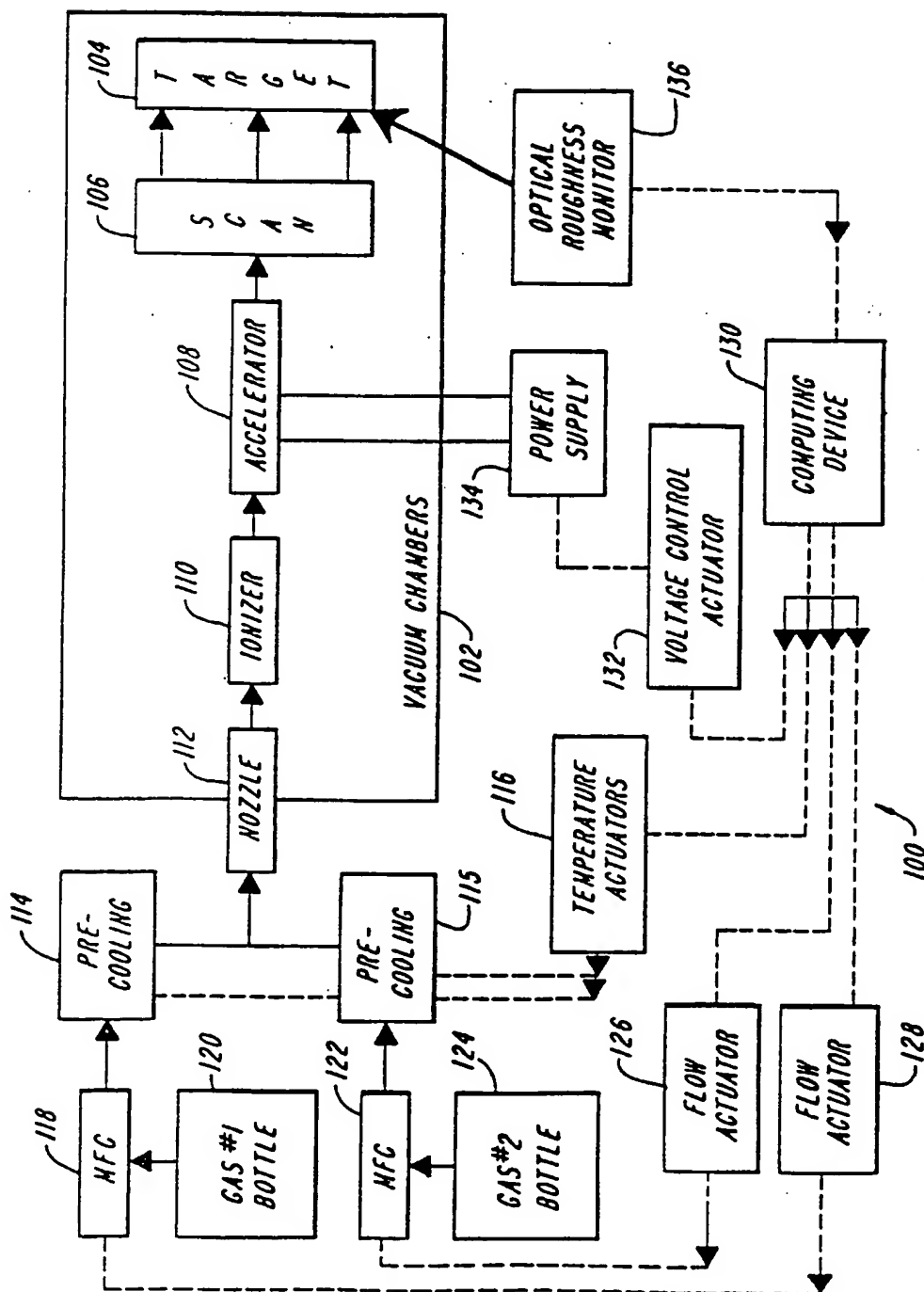


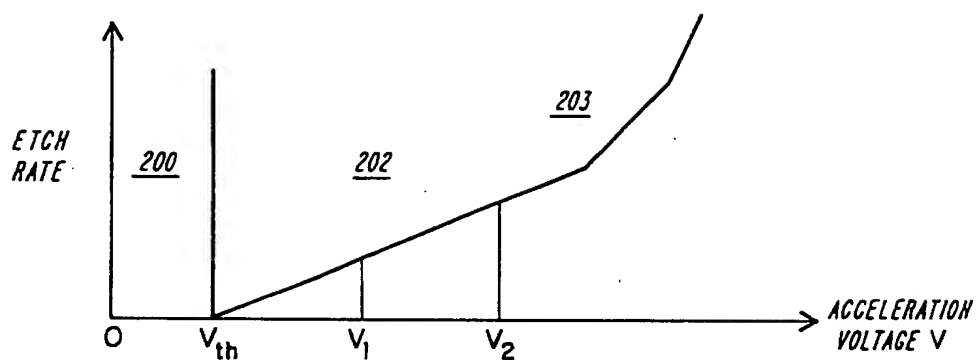
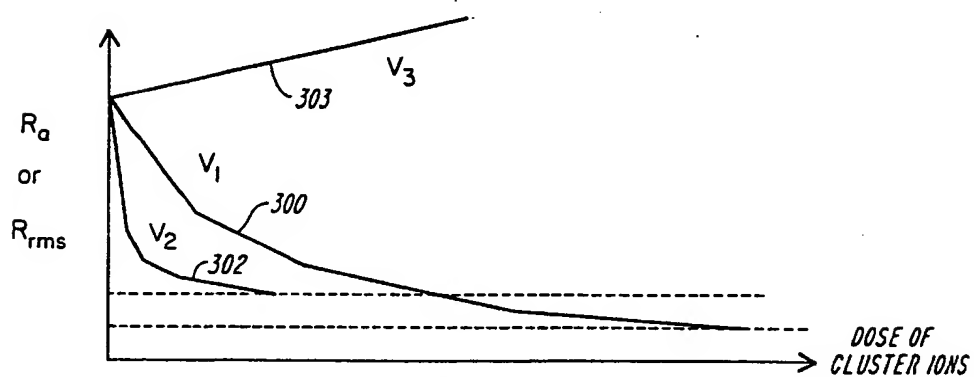
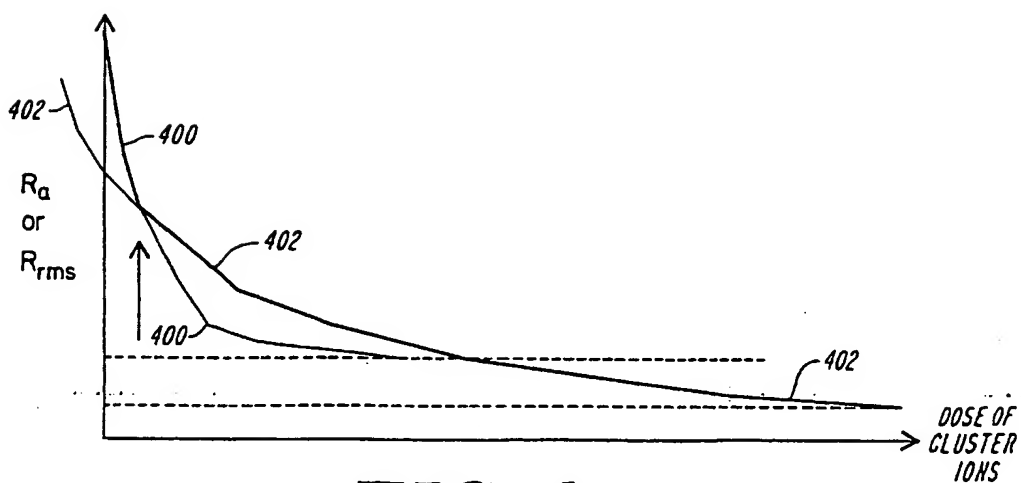
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**FIG. 1**

**FIG. 2****FIG. 3****FIG. 4**

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ADAPTIVE GCIB FOR SMOOTHING SURFACES

PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/144,524 filed Jul. 19, 1999.

BACKGROUND OF THE INVENTION

The invention relates to the field of gas cluster ion beam (GCIB) smoothing of surfaces.

Surfaces of microelectronic materials such as semiconductors, dielectrics and metals (often as thin films on a substrate) need to be smoothed after their fabrication by deposition, crystal growth, etching or similar processing. The close proximity of microelectronic components, either as multiple layers or as interacting/interconnected subcomponents requires a high figure of merit for surface quality.

Smoothing methods can be classed roughly as mechanical or chemical, and these are carried out in ambient, wet solution or in a vacuum-chamber environment. Ion beams are superior in several important respects to traditional lapping, grinding, sanding, acid/base etching, etc. In particular, the vacuum environment of the ion-beam apparatus provides contamination control for the workpiece surface that can not be attained with any wet or atmospheric-based methods. The ion beam (dry) etches, i.e., sputters, away the surface, and if the surface is initially rough the etching may reduce the roughness.

As the surface reaches a smoothness near that of the atomic dimensions of the material, the ion-beam smoothing capability reaches its intrinsic limit, i.e., its asymptotic value. That limiting amount of roughness is due to the basic or intrinsic nature of both the surface and the ion interaction with that solid surface. Unfortunately, the limiting roughness for conventional ion-beam etching methods is not sufficiently smooth to make possible many of the applications requirements that have been widely projected to be necessary for future generations of microelectronics and photonics.

It has been recognized by specialists working with ion-beam processing of surfaces that beams composed of clusters of gas atoms, roughly 100 to 10,000 atoms in each cluster, can be singly ionized, accelerated and upon impact with a surface provide superior smoothness of many materials. This is the GCIB method of etching and smoothing. The efficiency of this method is limited partly by the ion dose required to accomplish reduction of roughness to within desired limits. Ion cluster beams may be composed of various gas species, each with a range of etching and smoothing capabilities. Noble gas ion beams (such as argon) interact with a surface by physical means (called sputter etching) while other gas types (e.g., oxygen) beams will interact both physically and chemically, i.e., reactively.

The chemical ion etch is generally a faster etch, but is highly specific to the composition of the particular surface being etched. Much less composition specific, the physical ion etch will generally have the lower residual roughness for all kinds of surfaces, i.e., leave a less rough surface after an arbitrarily long exposure (high dose). Larger clusters will provide the highest final surface finish but their formation in a GCIB apparatus is less efficient such that the highest beam currents may not be attained with the largest clusters.

Beams of higher energy, occurring as a consequence of the use of a higher accelerating potential, etch faster, but are expected to have a higher residual roughness for the same

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cluster size or size distribution. The greater residual roughness is due to (shallow) implantation and effects referred to as ion mixing, which cause the ion beam to etch material from (shallow) subsurface regions. Higher beam currents (flux of clusters upon the surface) will also etch faster but may result in higher residual roughness than would lower beam currents as a consequence of nonlinear effects in the surface etching physics and stochastic phenomenon.

SUMMARY OF THE INVENTION

The invention provides a method and apparatus for adapting the nature of an ion beam during processing of the surface of a solid work piece so as to improve the reduction of surface roughness (smoothing) by using a GCIB. In addition, the invention provides surface smoothing in combination with etching to predetermined depths and surface contamination removal. Advantages are minimum required processing time, minimum remaining roughness of the final surface, and reduction in the amount of material that must be removed in order to attain a desired level of smoothness.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic block diagram of an adaptive cluster beam smoothing apparatus in accordance with the invention;

FIG. 2 is a conventional graph showing schematic etch rate (solid line) of cluster ion beam for various acceleration voltages, sequenced as $V_{a1} < V_{a2} < V_{a3}$;

FIG. 3 is a conventional graph showing progressive reduction of roughness with cluster dose at constant acceleration voltage for the cluster ion beam; and

FIG. 4 is a graph showing progressive reduction of roughness with cluster dose by an adaptive GCIB method in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

For smoothing a typical surface in a microelectronics application area with GCIB, the optimum final surface finish quality (smoothness) can be obtained with an argon beam at low acceleration voltage and low beam current. The time required to reach this optimal condition will be much longer than if other beam choices were made. The invention utilizes a hybrid or adaptive approach to GCIB. For example, the initial GCIB smoothing can be done by using a higher-energy beam (more acceleration) to remove (etch) as quickly as possible the initial surface with its greater roughness. During the etching, and as the roughness of the surface reaches the residual roughness limit for that beam energy, a GCIB apparatus can be adjusted so that the beam carries less energy and the etch process continued until it reaches its new and lower residual roughness limit.

FIG. 1 is a schematic block diagram of an adaptive cluster beam smoothing apparatus in accordance with the invention. The gas flow path and the cluster beam are shown as solid lines and the control paths are dashed lines. The arrows indicate the direction of flow for gas, clusters or information, respectively. The vacuum system is multiply chambered with individual pumps (not shown) for each. The optical path for the inspection of surface roughness is shown as a heavy line and arrow.

Apparatus 100 of FIG. 1 includes vacuum assembly 102 for generating the gas-cluster ion beam. A first gas, e.g., argon, is stored at high pressure in a gas bottle 120. The gas passes out through a mass-flow controller (MFC) 118 which consists of a diaphragm regulator and flow-measuring sensor

as well as means to feedback the flow information to the regulator, that being typically electronic in nature and adjustable by the system operator or computer acting on an instructional scheme. The gas then flows into a pre-cooling apparatus 114, that consists of a heat exchanger which is in turn cooled by a cryogenic means, such as circulating liquid nitrogen or the cold end of a closed-cycle (recirculated) refrigeration system. At least one additional gas may be mixed with the gas originating from the bottle 120. A second gas from a gas bottle 124 would pass through MFC 122, and pre-cooling apparatus 115 before mixing with the gas originating from bottle 120. The gas or gasses flow in a small-diameter tube, at a pressure of typically ten atmospheres, to a nozzle 112.

The nozzle 112 typically has a bore of 50 to 100 μm diameter and an exit cone with a small-solid angle of about 10° . Preferably, the shape of the exit cone on the nozzle is that of the Laval nozzle. The gas forms a supersonic jet and is adiabatically cooled by its expansion through the nozzle into the first vacuum chamber of the assembly 102. If the gas density falls slowly enough during its passage through the exit cone there is sufficient time for the cooled, supersaturated vapor to condense into droplet nuclei and grow, by aggregation, into small drops, i.e., large clusters of a few thousand gas atoms or molecules. This jet of clusters and residual gas is directed at a small opening in the first vacuum chamber wall and the core of the jet, which has the highest concentration of clusters, passes into the second vacuum chamber. The first chamber is maintained at a pressure of about 10 to 100 mTorr by a vacuum pump and the second chamber at a pressure of 10^{-5} Torr or less, by a second pump.

After entering the second chamber, the jet of clusters passes into the ionizer apparatus 110 and here into the core of a wire-mesh cage that is the anode of a low-energy electron beam, typically 100V. These electrons impact on the clusters and cause knock-off of electrons from the cluster, which in turn serve to ionize the clusters, typically with just one net positive unit of charge. The ionized clusters are extracted from the ionizer 110 by the first electrode element of the accelerator 108.

As a second component of the accelerator, there is an electrode with a large negative potential or voltage relative to that of the extractor electrode, that voltage difference being the acceleration potential. As a third component of the accelerator 108, there is a set of typically three electrodes that function as a converging lens and, upon appropriate choice of voltages for those electrodes, this lens serves to focus the cluster ion beam at a predetermined point downstream in the beam path. At that focus point on the beam axis the workpiece target 104 is located, it being perpendicular to the beam. Near but parallel to the ion beam path, and between the last electrode of the accelerator 108 and the target 104, are located fixed pairs of plates 106 that serve to electrostatically scan the beam by virtue of voltage differences between the plates. One pair of the plates when biased causes deflection of the beam within the horizontal plane while the second pair deflects in the vertical plane.

Electrical power supplies 134, external to the vacuum assembly 102, provide bias voltages and current to the various electrodes of the ionizer 110, accelerator 108, and scanner 106, within the vacuum chamber. Typically, a set of individual power supplies will be used, one for each electrode, and each independently controlled external to the assembly 134 by a voltage-control actuator 132. Simpler configurations can also be used, such as a single power supply with a resistor ladder network to divide out the required voltages. However, in the present invention, at least

one of the electrode voltages preferably will be individually adjustable according to the adaptive method. Various intermediate schemes with multiple power supplies may be utilized and provide some electrical advantage. All the electrodes may be driven by a set of supplies connected in parallel or series, or even combinations of these, as well as together with at least two electrodes driven from a resistor divider as well. Some of the supplies will internally regulate themselves by electronic means, to a set voltage or current, that set value being provided by the actuator 132, and preferably communicated by fiber-optic relay and electrical means. The optical-link relay is preferred since for some connection configurations, some of the power supplies 134 are operated at very high voltage above the ground or system-common potential.

Inspection and monitoring of the target 104 workpiece surface is preferred so as to provide a quick indication during the surface processing as to the extent to which the GCIB has accomplished its task, as expected within an allotted time. Means are provided in the invention by way of an optical roughness monitor 136 wherein an optical method of measurement is utilized, since it can do so while working well away from the normal incidence angle that the cluster beam requires and can do so without contact or disturbance to that workpiece surface. The strength of a laser light beam scattered, i.e., nonspecular reflection, from the target surface after glancing incidence is a useful indicator of surface roughness. Very fine-scale roughness will require short wavelength light, e.g., ultraviolet, for practical sensitivity. Access into the vacuum assembly 102 is provided by windows composed of material that is transparent at the wavelength utilized. The intensity of the scattered light, or other optical parameter, is measured by an optical detector within the monitor 136 and an electrical output provided to a central computing device 130.

Utilizing the signaled information from the monitor 136, the computing device 130 makes certain logical determinations. Those logical determinations are encoded into digital or analog signals and delivered to various actuators via signaling connections (shown as dotted lines from the computing device 130 to temperature actuators 116, flow actuators 126, 128, and voltage control actuator 132, thereby forming a control loop for the GCIB apparatus. The flow actuators 126 and 128 provide means to convert the signals from the computing device into mechanical or similar actuation that adjusts the set point for the mass-flow controllers 118 and 122, respectively. The temperature actuators 116 provide means to convert the signals from the computing device into actions that adjust the set point of the gas pre-cooling apparatus 114 and 115. In addition, the voltage-control actuator 132 provides means to electronically adjust the set point of operation for all the power supplies in the assembly 134.

The computing device 130 may utilize any of various schemes to arrive at the logical determinations that adapt the GCIB apparatus during its processing of each workpiece. The simplest is just a time chart that instructs voltage changes after specific time intervals following the start of the processing. The preferred algorithm would be a combined mathematical calculation from a detailed theoretical model (or approximation, etc.) of the curve shapes in FIG. 3 together with in-process information provided by the optical monitor 136. The mathematical calculation utilizes many curves of the shape 300 and 302 illustrated in FIG. 3 that show reduction in the roughness following an exponential decay to an asymptote.

Generally, only the three parameters of (1) the initial roughness, (2) the decay rate, and (3) the asymptote value,

are required to characterize each curve such as 300. By calibration of the apparatus under fixed operating conditions, the detailed knowledge can be found as to how etch rate and asymptote depend on the GCIB parameters such as acceleration voltage, cluster size, gas type and pre-cooling. With that information, which must be measured for each composition and type of workpiece, there will be a unique sequence of changes or adaptations in the GCIB apparatus that will provide the most rapid process to reach the best final asymptote with minimum surface roughness. In an exemplary embodiment, the computing device 130 will start with tabulated parameters of etch rate and asymptote predetermined for each workpiece material, find by calculation the fastest set of adaptations or sequence of GCIB-processing parameters, and then execute this sequence while utilizing process-monitor information to make minor adjustments for each individual workpiece.

More complex adjustment schemes for the beam energy will be preferred as they will even more quickly facilitate arriving at the desired surface quality. The beam energy in the invention is constantly under adjustment so that it is always proceeding toward the final finish desired (both etch depth and surface roughness) at the fastest rate possible for that stage of the etching.

Each composition of surface (material) will have at least a somewhat different interaction with each beam, and thus the optimal adjustment of the apparatus at each instant of the process will depend on the type of material being smoothed. For example, soft gold films will have a somewhat different physical ion-etch behavior under GCIB, due to the differing sputter mechanics at the atomic level, than will brittle and hard ceramics such as alumina. The invention provides a method and apparatus that is capable of optimizing the GCIB to each surface composition and to each initial surface roughness.

A further feature of the GCIB effect on surfaces is the removal of surface contamination. At acceleration voltages below the threshold value for the surface under process, the cluster ions impacting the surface do not appreciably etch the surface, but contaminants on the surface can be dislodged and thereby removed from the surface. Due to the generally weaker bonding energy (adhesive forces) of foreign contaminants compared with the stronger solid substrate material bonds (cohesive forces), it will be possible to select ion energies that are capable of breaking the former (ion energy greater than the adhesion) with little or no damage to the substrate (ion energy less than the cohesion). The invention provides a GCIB apparatus that can be adapted to operating conditions such that surface cleaning (decontamination) occur, and then adapted to etching and smoothing operating conditions. It is preferable that these are all utilized for each workpiece so that the final surface has been cleaned, etched down to the desired depth and left with a final surface roughness as low as possible.

The conventional GCIB smoothing process of ion etching can be improved by the adaptive technique of the invention. With a cluster-ion beam, the etch rate and steady-state level of residual roughness of the target object are largely independent parameters that are influenced by many factors. Practical use of GCIB smoothing will be greatly enhanced if the parametric effect of these factors is understood and manipulated by the processing method and configuration of the apparatus. For example, the time required to reach the optimal smoothness condition (minimal residual roughness) will be much shorter if the beam is adapted during the process, much as one might change from coarse to fine grit size when using sandpaper to smooth the surface of wood as

the surface becomes progressively smoother. As an alternate practical goal, it may be desired in the process to ion-beam etch through a certain given thickness of material at the maximum rate possible, such as in thinning a deposited layer so as to attain a desired final film thickness. After completing the desired etch depth, it will be of additional value to render that same and final surface as smooth as possible.

Each type (chemical composition and structure) of surface material (film, or bulk if it is exposed) will have an etching-onset threshold, an etch rate and steady-state residual roughness that is in general unique from other material types. FIG. 2 is a conventional graph showing schematic etch rate (solid line) of cluster ion beam for various acceleration voltages, sequenced as $V_{ph} < V_1 < V_2$. The acceleration voltage scale is divided into regions where different effects predominate. In region 200, the surface is cleaned by a low energy beam. In region 202, not too far above V_{ph} , a linear etch rate occurs. In region 203, which extends off-scale to high energy (voltage), enhanced etching will occur but the surfaces will not be smoothed.

These etch characteristics are a consequence of the microscopic details of the interaction of the ion beam and the unique material properties of the target material, whether the ions are single atoms, or molecules, or clusters of these. In addition to the kinetic energy of the ion beam, the size of the clusters (number of constituent atoms or molecules) and the state of condensed matter that the cluster is in at the time that it impacts the target surface, will effect the nature of the beam interaction with the surface. Conservation of momentum of the incident clusters is attained in several ways depending on features of the clusters and the surface, such as the size and energy of the cluster, the peak pressure and temperature caused by the collision, the stress-strain response of the cluster and surface including the extent of plastic deformation, the intensity of the acoustic shock wave generated within the cluster relative to the cluster fracture strength, and the extent to which the cluster and surface respond in an elastic manner, i.e., conserve the incident cluster energy.

Sputtering of pure elemental metals by monomer ions typically is found to etch only for ions above a threshold ion energy that is approximately proportional to the heat of sublimation for those metals. It is conventionally reported that the etching rate of metals by argon clusters increases approximately linearly with acceleration voltage above a threshold, that being about 5 to 7 kV for typical situations. FIG. 2 illustrates this threshold as well as a linearly increasing etch rate above the threshold. Also, it has been reported that gold films are etched to lower and lower amounts of roughness (measured as either average roughness R_a or root-mean-square roughness R_{rms}) as additional dose accumulates from an argon cluster beam. This situation is illustrated in FIG. 3, where the R_a or R_{rms} approach exponentially toward the minimum value attainable.

FIG. 3 is a conventional graph showing progressive reduction of roughness with cluster dose at constant acceleration voltage for the cluster ion beam. Three etch curves are shown, one 300 done at voltage V_1 and the other 302 at V_2 , with $V_1 < V_2$. The curve 303 for V_3 , with $V_3 \gg V_2$ is etching at such a high voltage that the surface is made rougher. The curves are drawn in segments for illustrative purposes, but in reality would be smoothly curving. The curve 302 at V_2 is the most steeply declining but has an asymptote at a higher R_a than does the curve at V_1 , while the latter is slower to decline, but has the lowest R_a for high dose.

A mathematical model is reported together with computer simulations of cluster etching using that model. A simulated

etching was found to depend on acceleration voltage or energy, with increasing etch rate at increasing energy, but with asymptotic roughness (at very high dose) that decreased with increasing energy. The invention provides that this can not be the outcome under realistic ion-etching conditions. The residual roughness that remains after an ion etch for a very long time, hence a high dose, will certainly depend on the extent to which cluster impacts with the surface of the workpiece penetrate the surface and sputter off material that originates from below the immediate surface region. This is illustrated schematically in FIG. 3, where the asymptotic (high dose) roughness (R_a and R_{ms}) of the lower voltage (V_1 , with $V_1 < V_2$) is itself smaller.

Conventional measurements of atom, molecule and cluster ion impact and etching show a trend toward decreasing depth penetration and disruption as the ion energy is reduced, until that energy reaches the minimum or threshold required for an etching to occur. Measured depth profiles of the concentration of the incident ion species below the surface of the workpiece indicate this trend quite clearly. The invention provides that with cluster etching the asymptotic roughness at high dose will be at a minimum for etching with cluster ion beams accelerated to energies just above the threshold for etching. The threshold energy can be assessed experimentally for each type of workpiece material and for each composition, thermodynamic state and acceleration of the cluster beam.

An adaptive GCIB etching process in accordance with the invention is illustrated in FIG. 4. FIG. 4 is a graph showing progressive reduction of roughness with cluster dose by an adaptive GCIB method in accordance with the invention. Etching begins at curve 400 with clusters constantly at V_2 , then abruptly changes to curve 402, at a dose where the vertical arrow is located. Both curves 400 and 402 are extended before and after the crossover point by curved dotted lines. Etching continues along curve 402 at constant voltage V_1 , with $V_1 < V_2$. The combined etch curve (solid lines only) is the adaptive method. Asymptotes for etching at V_1 and V_2 are shown as horizontal dashed lines.

The etch begins with a larger acceleration voltage V_2 , approximately 20 kV to 60 kV, causing a relatively rapid etch rate, and a dose to the workpiece is accumulated until the R_a or R_{ms} is reduced by some significant amount. The acceleration voltage is then reduced to V_1 , approximately 5 kV to 7 kV, (shown as a kink or abrupt bend in the etching curve) and the exposure continues until a large enough dose accumulates such that the exponential curve is well toward its asymptotic value. The single etch curve can be seen as essentially a piecewise combination of the two curves. It is important to notice that this two-step adaptive process provides rapid reduction of roughness early on when the workpiece surface is at its roughest, but then adapts to a lower voltage since the higher value will not provide the desired small asymptotic roughness. As an adaptive method, multiple steps in the voltage would be even more efficient of the exposure time as would continuously changing acceleration voltages.

As an example of adaptive GCIB, a sequence of system operational conditions is described based on known etching parameters, as well as desired final etch depth and maximum surface roughness. Toyoda et al. report in proceedings of the conference "Applications of Accelerators in Research and Industry", edited by Duggan and Morgan (Amer. Inst. Physics Press, New York, 1997), on page 483, that argon cluster-ion beam etching of copper films on silicon wafers has an approximate threshold voltage V_{th} =6,000 V, and a sputtering yield Y that is linearly proportional to the cluster acceleration voltage V above V_{th} , according to

$$Y = (4.2 \times 10^{-3})(V - V_{th}) \text{ in units of sputtered atoms per incident ion.}$$

From the yield Y the etch depth d , can be calculated by using the following expression:

$$d = (DY)/\rho_a \text{ in units of cm,}$$

and where D is the cluster-ion dose density, $D = It/e$, for J the ion-beam current density (A/cm^2), t the exposure time, e the elemental charge $e = 1.6 \times 10^{-19}$ coulombs, and ρ_a the atomic density of the solid (atoms/cm³). Hence:

$$d = (4.2 \times 10^5)(V - V_{th})D/\rho_a \text{ in units of } \text{\AA}.$$

For example, the density of atoms in solid copper is $\rho_a = 8.5 \times 10^{22}$ atoms/cm³. If the ion beam in this example has $J = 10 \mu A/cm^2$ and $V = 27$ kV, then with $t = 1$ sec of exposure, the etch depth is expected to be about $d = 6.5 \text{ \AA}$, or in about $t = 1$ hour of exposure $d = 2.3 \mu m$.

The etch depth d calculated here is the depth between two ideally flat surfaces or the average depth between two rough surfaces. Clearly a measured d is more statistically meaningful if the average roughness R_a of the higher and the lower surfaces are both much smaller than d , i.e., $R_a < d$. It is a general feature of the GCIB process that the cluster ions reduce the surface roughness (R_a) upon impact at normal incidence. Yamada et al. have reported on the roughness reduction process in The Journal of Vacuum Science and Technology, Volume A14, page 781, 1996. There the reduction in R_a is reported to occur in an exponential fashion with dose density D , nominally as:

$$R_a = (R_i - R_o) \exp(-D/\Delta) + R_o$$

where R_i is the initial roughness of the surface, R_o is the asymptotic or limiting roughness attained after arbitrarily long exposures, and Δ is the exponential dose characteristic for roughness reduction. (This exponential function is that illustrated in FIG. 3, as curves 300 and 302.) For thin films of copper that had been fabricated on silicon wafers, an argon cluster-ion beam with 20 kV of acceleration was reported to smooth a film with initial $R_i = 58 \text{ \AA}$ toward an estimated $R_o = 12 \text{ \AA}$, requiring a dose of about 1×10^{15} ions/cm² to reach $1/e$ (=37%) of the quantity ($R_i - R_o$). Hence $\Delta = 1 \times 10^{15}$ ions/cm² for this situation.

Further, it is estimated here that $R_o = \alpha(V - V_{th})$ with approximately $\alpha = 1 \times 10^{-3} \text{ \AA/V}$, and $\Delta = \beta/(V - V_{th})$ with approximately $\beta = 1.4 \times 10^{19}$ ions/cm². Both of these linear relations assume that the acceleration V is larger than, but not too much larger than V_{th} , i.e., V must be greater than V_{th} and less than about 100 kV. It can also be seen that as V approaches V_{th} , then the residual roughness (R_o) and both the rates of smoothing ($1/\Delta$) and of etching (d/t) all tend toward zero, which is a primary motivation for the adaptive-GCIB invention. This example is further developed by extension to mixed gasses for forming the cluster beam, and in particular the example that the pure argon gas is replaced by a mixture of argon and oxygen gasses at a volume ratio of 80:20. For this it is estimated that the etching of the copper film will be accelerated about threefold, hence $Y_m = 3Y$ and $\Delta_m = \Delta/3$, but that the asymptotic roughness (that after very long exposures) will increase twofold, hence $R_{om} = 2R_o$, where each of Y , Δ and R_o are the values for pure argon gas, calculated as above.

A possible scenario for an adaptive-GCIB process to smooth and etch a thin-film surface is illustrated by the following sequence of apparatus operational parameters. The particular workpiece in this example is composed of a copper film that has an initial surface roughness of $R_i = 100$

\AA , and responds to the GCIB according to the various parameters and their numerical values shown in Table 1, below. The film is processed with four sequential GCIB exposures, each one of which reduces the film roughness and etches away a certain thickness of the film. The four sets of operational conditions and the film roughness and etch depth are tabulated in Table 2, below.

Briefly, step one comprises an aggressive etch with a gas mixture and high acceleration voltage, followed by a re-measurement of the surface roughness in-situ (using laser-light scattering). Step two comprises pure argon etching at that high voltage, step three reduces the voltage somewhat, and finally step four completes the process sequence with pure argon and an acceleration voltage only somewhat above that of the threshold energy.

The in-situ measured R_a in each case are accomplished after the GCIB exposure in each step, and then used as the basis for calculating the expected effect of the next exposure step. In this example, the apparatus is operated at a constant cluster-ion beam current (J) for all of the steps illustrated. Thus, the exposure time (t) can be calculated from the dose (D) indicated for each step.

TABLE 1

Parameters for example of adaptive-GCIB process.		
Parameter	Symbol	Numerical Value
Film density	ρ_s	8.5×10^{22} atoms/cm ³
Initial roughness	R_i	100 \AA
Threshold energy	V_{th}	6,000 V

TABLE 2

Operational conditions and stepwise changes in the film during adaptive process.					
Operation	Initial	Step # 1	Step # 2	Step # 3	Step # 4
Gas to form cluster-ion beam	—	Ar + O ₂	Ar	Ar	Ar
Acceleration Voltage V	—	30 kV	30 kV	20 kV	10 kV
Sputter Yield Y	—	300	100	60	17
Dose	—	2×10^{14}	6×10^{14}	1×10^{15}	3.5×10^{15}
Characteristic Δ (ions/cm ²)	—				
Dose D, this step (ions/cm ²)	—	1×10^{14}	5×10^{14}	1×10^{15}	5×10^{15}
Asymptotic R_a (\AA)	—	50	25	15	5
Calculated Process R_a (\AA)	—	80	47	27	10
In-Situ Measured R_a (\AA)	100	75	—	—	11
Etch Depth d, this step (\AA)	0	36	59	69	100
Etch Depth, cumulative (\AA)	0	36	95	164	264

By way of illustrating the advantage of the adaptive process, it is noted that of the four steps, only step four has the ability to reach the final roughness R_a that the sequence shown in Table 2 did. If only a single process is used for comparison and, except for dose, the operational conditions were those listed for step four, a larger dose of 9.7×10^{15} ions/cm² would be required. This single-process dose is 1.5 times larger than the four-step process illustrated in Table 2. If the GCIB apparatus operates at a cluster-ion beam current of $J=10 \mu\text{A}/\text{cm}^2$ for all of the processes in this example, then the adaptive process would require a total exposure time of

106 sec and that of the single process 155 sec. Hence, the advantage of the adaptive process of the invention.

As an example of the significance of the etching threshold, consider that at low incident energy of a cluster beam onto a surface under highly elastic conditions, there may be only weakly irreversible effects and the clusters will bounce elastically without fracturing (etching) any of the surface material or even themselves. As another example, clusters of larger size can be formed from a given gas, e.g., argon, by pre-cooling that gas, e.g., using cryogenic methods, or by mixing in a high concentration of a lighter gas, e.g., hydrogen or helium, which subsequently is pumped away in the vacuum chambers well before cluster impact. At the same ion-cluster acceleration voltage, all singly charged clusters generated will have the same kinetic energy. But the larger clusters in this example will have a lower momentum and velocity and less average kinetic energy per constituent atom. The combination of these parameters will effect the nature of the collision impact with the target surface and hence the etching.

At relatively high cluster-impact rates (number of cluster collisions per second), and hence etching rates, the impact, sputter and etching processes may well become nonlinear or more nonlinear than at lower rates. As a consequence, etching at high beam currents (number of ions per second, with each ion being essentially one cluster) may increase nonlinearly. According to the invention, the high etch rate may be useful in the initial stages of an etch to smooth the surface of a workpiece, but the final residual roughness of the surface will be positively affected if the beam current is reduced toward the end of the etch process to the point that the etch mechanisms are more nearly linear.

Clusters, as small pieces of matter in a condensed physical state, have a thermodynamic state, may be liquid or various solid forms, and have a temperature. During transit through the vacuum chamber from formation in the nozzle apparatus until impact with the target surface, the clusters will evaporate some of their material as they tend toward thermodynamic equilibrium with the ambient vacuum. This evaporation will result in evaporative cooling and a reduction of the cluster temperature.

For argon, as an example, the solidification temperature is only a little lower than the liquid condensation temperature, and thus it is expected that under most conditions an argon cluster impacts a target surface in the solid state. The viscous-flow and elastic nature, including the fracture strength, of solids depends on many parameters including the bond strength, the presence of crystalline material and nature of crystal defects or polycrystallinity, as well as the temperature. Liquid and solid argon are bonded by van der Waals forces, which are characterized by very weak attractive forces and very strong (hard core) repulsive forces.

For acceleration not too far above the threshold, the etching effects of the impact of a very cold gas-cluster beam will be greater than that of a nearly melted (and hence soft) solid cluster or that of clusters in the liquid state. This is evidenced by the considerably increased abrasive and eroding effects of a jet of ice crystals onto a surface compared with that of a water jet. Ice, however, is bonded much stronger than is solid argon. Generally, the GCIB smoothing process will be enhanced by apparatus able to create clusters in different states and temperatures as well as processing methods that utilize these features to improve the practical application of this smoothing.

Vacuum-based, dry etching with ion beams is especially well suited to microelectronic circuit manufacturing by batch processes on large diameter wafers, e.g., silicon. Here

it is often the situation that the surface which must be etched (or film that must be thinned) must also be rendered smooth, i.e., of lower roughness. The use of GCIB is particularly advantageous for such applications, since it represents a substantial advance in the art over conventional ion etching methods. As with all methods of ion etching, each composition of matter in the surface of the workpiece may exhibit an etch rate distinct from that of other compositions.

For example, the surface may include lithographically patterned metal films that are intended as circuit wiring in VLSI or as ferromagnetic sensors in hard-disk memory heads, and these are separated, according to the pattern, by dielectric film materials such as a silicon-oxide or aluminum-oxide compounds. It is often desired then to thin these two-component surfaces, i.e., metal and oxide films, in such a manner as to not cause any height or thickness differences between the two components. Or, if height differences already exist, to reduce or eliminate these, i.e., to planarize the surface. Control of differential etch rates can provide an improved result for planarization etching, but adaptation of the etch apparatus to each material and stage of the process will be required for this advantage to be realized.

The etch rates of any two materials will in general depend on both their physical and chemical etching or sputtering rates, which in turn depend on the composition and energetics of the ions used in the process. For example, argon as an inert gas only etches by physical sputtering means, while oxygen ions incident onto an oxidizable metal surface can etch both physically and chemically depending on the ion energy and other parameters. At high energy, all ions tend to etch predominately by physical sputtering, but just above the threshold energy chemical effects usually dominate. The various methods of dry chemical etching of surfaces by ions are often referred to as reactive-ion etching (RIE). Halogens and gas-phase compounds containing halogens are also well known in the art of ion etching to have selectively higher etch rates on the surfaces of certain materials.

Gas cluster ion beams have the property of etching by physical and chemical means much as do conventional monomer ion beams. The invention provides a method and apparatus to improve the planarity of two-component surfaces as an additional and intended consequence of the GCIB smoothing process. The clusters themselves can be formed in a mixed-gas solvated composition of, for example, argon with a few percent of oxygen or chlorine. If the source gas supplied to the nozzle consists of both argon and oxygen with the latter at a high percentage, that being greater than about 20%, the two gasses will generally each form clusters but with primarily only one or the other gas type in those clusters.

GCIB with either the solvated-mixture clusters or the mixture of distinct clusters can be utilized for etching two-component surfaces, and, under suitable conditions render those surfaces planar and extremely smooth. In addition, the GCIB with pure argon can be chemically assisted by injecting a small stream of the chemically reactive gas, such as oxygen or chlorine, at or near the workpiece surface. This is an improvement on earlier methods of chemically-assisted ion-beam etching (CAIBE) known and utilized, for example, to etch crystal-facet mirrors on compound-semiconductor laser diodes.

The optimal process and adjustment of the apparatus will generally be possible by changing the beam parameters of the apparatus as the smoothing process is underway, and will further be possible by an immediate knowledge of the remaining roughness and etch depth of the target surface.

Thus, it is most desired for the invention to utilize instrumentation that is able to provide direct and immediate information about the roughness and depth of the target workpiece during the ion-beam processing, i.e., in-situ process monitoring.

Furthermore, apparatus capable of modification of the ion-beam characteristics during the process will be essential to adapt the process during the period of execution of that smoothing process. In addition, an automated computing mechanism that can apply decision algorithms based on information provided by the in-situ process monitor and provide subsequent instructions to electromechanical actuators on the ion-beam-forming apparatus will make possible a closed-loop process control and a preferred adaptive smoothing of the workpiece. These features are illustrated with respect to the apparatus 100 of FIG. 1.

A great number of methods and variety of instruments are available for surface metrology. Many of these have been demonstrated as suitable for in-situ process monitoring of a workpiece within a vacuum chamber. Optical techniques are particularly well suited for this application. The wavelengths must be chosen so as to efficiently propagate through the gasses within the vacuum chamber and to be maximally sensitive to the surface characteristics that are to be monitored in each process. For example, grazing incidence of a laser beam will reflect off of a surface and generate a speckle pattern, i.e., small-angle scattering, that is sensitive to roughness of the surface at length scales from a few wavelengths down to a small fraction of the wavelength. If the incident optical beam is polarized and the polarization of the reflected beam is analyzed then the surface roughness is expressed by the ellipsometric parameters Ψ and Δ . Electron beam instruments are also well suited and reflection high-energy electron diffraction (RHEED) has seen wide use for characterization of surface crystallinity and, to a lesser extent, roughness. X-ray beams can also be utilized.

The cluster-beam accelerator functions by way of a high electric potential difference (voltage) between electrodes in the vacuum chamber. The potential is driven by a power supply external to the vacuum chamber. Electronic power supplies are preferred, and further, those that provide a means for controlling the strength of the acceleration potential (voltage) by way of a low-level relay potential are preferred. The relay potential is supplied remotely and adjusted by the operator of the GCIB apparatus or preferably by direct analog output of a digital-computing device. The cluster size can likewise be controlled and adjusted by the operator or computer via electromechanical gas-flow valves, gas-pressure regulators and cryogenic cooling apparatus including heat exchangers. The first two means are used for adjusting the main gas source for forming clusters, e.g., argon, and for mixing a second or lighter gas and subsequent enhancement of the clustering action within the nozzle.

The cryogenic cooling means typically utilizes the flow control of a cryogenic fluid such as liquid nitrogen (sufficient to liquefy argon) acting on the cluster source gas, e.g., argon, by way of a heat exchanger. Cooling of the gas must be controlled since the condensation thermodynamics of that gas in the nozzle will change rapidly as the gas is pre-cooled to nearer and nearer the bulk liquefaction temperature. Often an electronic temperature regulator is employed and this is more effective if an electrical heating element is provided in the heat exchanger region so as to provide a more rapid response and more tightly controlled temperature-regulation conditions. The temperature set point of the regulator is best put under electronic control and incorporated into the adaptive control electronics, thus allowing the cluster sizes to be adapted during the etching process.

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Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

1. An apparatus for processing a surface of a workpiece utilizing an adaptive gas cluster ion beam, the apparatus comprising:

- a means for forming a gas cluster ion beam;
- a means for supplying and controlling one or more gases to the means for forming a gas cluster ion beam;
- at least one power supply, the power supply being connected to the means for forming a gas cluster ion beam; and
- a means for controlling the means for forming a gas cluster ion beam, the gas supply means, and the at least one power supply, to form a gas cluster ion beam with an initial etching rate wherein the initial etching rate transitions into at least one other etching rate, the at least one other etching rate being lower than the initial etching rate.

2. The apparatus of claim 1 wherein the controlling means further comprises, a means for implementing a predetermined schedule of exposures to control the transition from the initial etching rate to the at least one other etching rate and/or a means for monitoring the etching rate or surface roughness of the workpiece to initiate the transition from the initial etching rate to the at least one other etching rate.

3. The apparatus of claim 2 wherein the controlling means, controls the transition from the initial etching rate to the at least one other etching rate by controlling the at least one power supply to vary a beam acceleration voltage and/or current.

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4. The apparatus of claim 2 wherein the controlling means, controls the transition from the initial etching rate to the at least one other etching rate by controlling the at least one power supply to vary a voltage and/or current to the means for forming a gas cluster ion beam.

5. The apparatus of claim 4 wherein the controlling means, controls the transition from the initial etching rate to the at least one other etching rate by controlling one or more of the at least one power supply, temperature control means, or the gas supply means to vary one or more of a beam acceleration voltage and/or beam current, temperature of the gases, and ratio and/or composition of the gases.

6. The apparatus of claim 5 wherein the controlling means, controls the transition from the initial etching rate to the at least one other etching rate by controlling one or more of the at least one power supply, temperature control means, or the gas supply means to vary one or more of a beam acceleration voltage and/or beam current, temperature of the gases, and ratio and/or composition of the gases.

7. The apparatus of claim 2 wherein the controlling means, controls the transition from the initial etching rate to the at least one other etching rate by controlling the gas supply means to vary a ratio and/or composition of the gases.

8. The apparatus of claim 2 wherein the workpiece is composed of two or more surface compositional domains, and the controlling means controls the gas supply means to vary a ratio and/or composition of the gases to maintain the minimum difference in the etch rate of the domains thereby causing said surface to be made more planar from domain to domain.

9. The apparatus of claim 1 wherein the surface is initially decontaminated prior to the etching phase.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,375,790 B1
DATED : April 23, 2002
INVENTOR(S) : David B. Fenner

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,

Line 4, a new first paragraph should read:

-- STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND
DEVELOPMENT

This invention was partially made with U.S. Government support from the U.S. Department of Commerce under a NIST-ATP Cooperative Agreement No. 70NANB8H4011. The U.S. Government has certain rights in the invention. --

Signed and Sealed this

Sixth Day of May, 2003

A handwritten signature in black ink, appearing to read "James E. Rogan", with a horizontal line drawn underneath it.

JAMES E. ROGAN
Director of the United States Patent and Trademark Office